QoE Assessment in Haptic Teleoperation Systems: Position-Position versus Position-Force

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Abstract: In this paper, we make a comparison of haptic control schemes (position-position and position-force control schemes) for two haptic teleoperation systems by QoE (quality of experience) assessment. One is a remote control system with haptic media and video. In the system, we can write characters by controlling a haptic interface device at a remote place with another haptic interface device while watching video. The other is a remote instruction system with haptic media, video and voice. By using the system, a teacher can actively write characters and teach a student how to write the characters. The student can also write characters actively, and the teacher can confirm how the student writes the characters. We investigate the influences of network delay on QoE for the two systems with the two haptic control schemes.

Key words: Remote control system, remote instruction system, haptic control schemes, haptic media, video, voice, QoE (quality of experience), network delay.

1. Introduction

Recently, applications with haptic media are actively researched and developed in various fields such as the medical, robot control, artistic, educational and entertainment fields [1-3]. In this paper, we deal with two haptic teleoperation systems: a remote control system with haptic media and video [4], and a remote instruction system with haptic media, video and voice [5]. In the former system, a user of the master terminal controls a haptic interface device of the slave terminal with another haptic interface device of the master terminal while watching video. In the latter system, a teacher of the master terminal can actively write characters and teach a student of the slave terminal how to write the characters. The student can also write characters actively, and the teacher can confirm how the student writes the characters and correct the student’s mistakes.

There are at least two haptic control schemes for haptic teleoperation systems [6-7]. One is the position-position control scheme, and the other is the position-force control scheme. In the former, the master and slave terminals transmit the positional information of haptic interface device to each other. In the latter, the master terminal transmits the positional information to the slave terminal, which transfers the force information to the master terminal. The position-position control scheme has a problem that as the network delay becomes larger, the gap between the position of a haptic interface device at the slave terminal and that of the master terminal increases, and the reaction force becomes stronger. On the other hand, in the position-force control scheme, the reaction force is not larger than that of the position-position control scheme; however, the position-force control scheme has a problem that the direction of the reaction force presented at the master terminal may largely differ from that when there exists no network delay. Therefore, it is important to investigate the influences
of network delay for the two haptic control schemes quantitatively by QoE (quality of experience) [8] assessment.

In Refs. [4-5, 9-11], the position-position control scheme is used. The authors have built the remote control system [4], the remote instruction system [5], the networked penalty shootout system [9] and the haptic media, sound and video transmission system [10], and they have examined the influences of the network delay and media synchronization error on QoE.

In Ref. [11], a haptic interface device and a voice coil actuator, which is a device that converts an electric signal into the vibration, are connected, and methods for transmitting the feeling of touch to the surface of an object are compared. As a result, it is shown that there is room for improvement in each method.

In Refs. [12-13], the position-force control scheme is employed. In Ref. [12], Kim and Ryu propose the Energy-Bounding Algorithm (EBA) for enhancement of the position-force control scheme. They also investigate the behavior of a haptic interface device when they press the cursor of the device on a wall in a virtual space. Their experimental results show that the position and the reaction force can be kept constant in EBA, but they cannot be kept constant when EBA is not used. This means that EBA is effective. In Ref. [13], Lee et al. propose an improvement method of EBA by taking account of the network delay jitter. In the proposed method, the reaction force presented at the master terminal is almost the same as that at the slave terminal.

In Refs. [6-7], both haptic control schemes are handled. In Ref. [6], Lawrence analyzes the control schemes in terms of transparency and stability. He also makes a comparison among the position-position control scheme, position-force control scheme and “Passivated” position-force control scheme [6]. As a result, it is shown that the transparency and stability are low in the position-position and position-force control schemes; in the “Passivated” position-force control scheme, the transparency cannot be improved, but the stability is high. In Ref. [7], Lau and Wai construct a haptic transfer system with two different haptic interface devices and implement the position-position and position-force control schemes. They measure the position and reaction force of each haptic interface device. As a result, they show that the haptic interface device at the slave terminal accurately follows the movement of the haptic interface device at the master terminal in the position-position control scheme. It is also shown that the reaction force presented at the master terminal is almost the same as that at the slave terminal, but the gap between the positions of haptic interface devices at the master and slave terminals in the position-force control scheme is larger than that in the position-position control scheme.

However, in Ref. [4-7, 9-13], the influences of the network delay are not compared between the two haptic control schemes. It is important to compare the influences of the network delay since they may be dependent on the type of haptic control scheme.

In this paper, we apply the position-force control scheme to the remote control system [4] and the remote instruction system [5], which has been constructed with the position-position control scheme. We also make a comparison of the two control schemes for the two systems by QoE assessment. We further investigate the influences of the network delay on QoE.

The rest of this paper is organized as follows: Section 2 outlines the remote control system and the remote instruction system; section 3 explains the two haptic control schemes; section 4 describes assessment environments such as assessment systems and methods and assessment results are presented in section 5; section 6 concludes the paper.

2. Haptic Teleoperation Systems

2.1 Remote Control System

Fig. 1 shows the configuration of the remote control system. A user of the master terminal remotely controls a haptic interface device of the slave terminal by using another haptic interface device of the master terminal.
Fig. 1 Configuration of remote control system.

Each of the master and slave terminals has PHANToM Omni [14] (just called PHANToM here) as a haptic interface device. A whiteboard marker is attached to the PHANToM stylus at the slave terminal, and moving parts of PHANToM which are irrelevant to positional information are fixed by tapes. By doing so, the slave terminal’s PHANToM stylus becomes possible to write characters without holding the stylus by hand. There is a whiteboard sheet in front of PHANToM at the slave terminal. Also, a video camera is connected to each terminal, and the user of the master terminal writes characters on the whiteboard sheet while watching video. For details of the system, the reader is referred to Ref. [4].

2.2 Remote Instruction System

We show the configuration of the remote instruction system [5] in Fig. 2. The system consists of a teacher terminal (the master terminal) and a student terminal (the slave terminal). Each terminal has PHANToM as a haptic interface device. A whiteboard marker is attached to the PHANToM stylus at each terminal in the same way as that in the remote control system. A teacher remotely controls a haptic interface device and can instruct a student how to write characters by transmitting the sense of force. The student also can write characters actively, and the teacher can confirm how the student writes the characters and correct the student’s mistakes. Also, a video camera is connected to each terminal. When the teacher actively writes characters, he/she teleoperates PHANToM and instructs the student while watching video that projects the whiteboard sheet at the student terminal. When the student actively writes characters, he/she does the characters while watching video that projects the whiteboard sheet at the teacher terminal. The teacher or student who does not actively write the characters only holds PHANToM in the QoE assessment. A headset is connected to each terminal (We do not use the headset in the assessment as described in subsection 4.2.2); the teacher can instruct the student how to write the characters with voice, and the student can also ask the teacher.

3. Haptic Control Schemes

In the position-position control scheme, the two terminals transmit the positional information of PHANToM to each other. In the position-force control scheme, the master terminal (the teacher terminal) transmits the positional information of PHANToM to the slave terminal (the student terminal), which transfers the information about the reaction force calculated at the slave terminal to the master terminal. In what follows, we explain how to calculate the reaction forces presented at the master and slave terminals for the two haptic control schemes.
In the two haptic control schemes, the reaction force \( F_t^{(s)} \) which is output against PHANToM of the slave terminal at time \( t (t > 0) \) is calculated as follows:
\[
F_t^{(s)} = K_s(M_t^{(s)} - S_t^{(s)}) + K_d(\dot{M}_t^{(s)} - \dot{S}_t^{(s)}) \tag{1}
\]
where \( K_s \) is the spring coefficient [15], \( K_d \) is the damper coefficient [15], \( S_t^{(s)} \) is the position vector of the slave terminal at time \( t \), \( M_t^{(s)} \) is the position vector received from the master terminal at time \( t \), \( \dot{S}_t^{(s)} \) is the velocity of PHANToM at the slave terminal, and \( \dot{M}_t^{(s)} \) is the velocity of PHANToM calculated from the positions received from the master terminal. In this paper, we set \( K_s = 5.0 \times 10^{-2} \text{ N/mm} \) and \( K_d = 5.0 \times 10^{-4} \text{ N-ms/mm} \). These values were determined by a preliminary assessment so that we could move PHANToM comfortably when the network delay was very small.

In the position-position control scheme, the reaction force \( F_t^{(m)} \) output against PHANToM of the master terminal at time \( t \) is given by
\[
F_t^{(m)} = K_s(S_t^{(m)} - \dot{M}_t^{(m)}) + K_d(S_t^{(m)} - \dot{S}_t^{(m)}) \tag{2}
\]
where \( M_t^{(m)} \) is the position vector of the master terminal at time \( t \), \( S_t^{(m)} \) is the position vector received from the slave terminal at time \( t \), \( \dot{M}_t^{(m)} \) is the velocity of PHANToM at the master terminal, and \( \dot{S}_t^{(m)} \) is the velocity of PHANToM calculated from the positions received from the slave terminal.

In the position-force control scheme, let us denote the reaction force at the master terminal by \( F_t^{(M)} \) and the reaction force received from the slave terminal by \( F_t^{(S)} \) at time \( t \). \( F_t^{(M)} \) is calculated as follows:
\[
F_t^{(M)} = -K_g F_t^{(S)} \tag{3}
\]
where \( K_g \) is the gain coefficient [7] (we set \( K_g = 1.0 \) in this paper). Note that \( F_t^{(S)} = F_t^{(s)} \) if there were no network delay. However, generally \( F_t^{(S)} \neq F_t^{(s)} \) since there exists the network delay actually.

4. Assessment Environments

Here we explain our assessment systems and QoE assessment methods for the remote control system and the remote instruction system.

4.1 Assessment Systems

4.1.1 Remote Control System

As shown in Fig. 3, the master and slave terminals are connected to each other through a network emulator (NIST Net [16]) by using Ethernet (100BASE-TX) cables. We generate a constant delay for each packet transmitted between the master and slave terminals by using NIST Net.

In the position-position control scheme, the master and slave terminals transmit haptic Media Units (MUs), each of which consists of 40 bytes, to each other by User Datagram Protocol (UDP). Each haptic MU includes the sequence number and the positional
information. In the position-force control scheme, the master terminal transmits haptic MUs to the slave terminal in the same way as that in the position-position control scheme. The slave terminal transmits haptic MUs, each of which also consists of 40 bytes, to the master terminal by UDP. Each haptic MU transmitted from the slave terminal to the master terminal includes the sequence number and the information about the reaction force output at the slave terminal.

Also, the slave terminal transmits video MUs, each of which consists of 4,000 bytes, to the master terminal. The resolution of video is $320 \times 240$ pixels. The coding method of video is Moving Picture Experts Group phase 1 (MPEG-1) [17], and the video consists of only intra-coded pictures (I-pictures) [17]. The transmission rate of haptic media is 1000 MU/s, and that of video is 30 MU/s. The bit rate of haptic media is 320 kbps, and the average bit rate of video is 960 kbps. Each terminal carries out intra-stream synchronization control [18] over received MUs. We adopt Skipping [19] for the intra-stream synchronization control. Skipping outputs MUs on receiving the MUs. However, when multiple MUs are received at the same time, Skipping outputs only the latest one and discards the others. Furthermore, Skipping discards a received MU when the sequence number of the received MU is smaller than that of the last-output MU.

4.1.2 Remote Instruction System

As shown in Fig. 4, the teacher and student terminals are connected to each other through NIST Net by using Ethernet cables. NIST Net is also used to generate a constant delay for each packet transmitted between the two terminals.

Haptic MUs are transmitted in the same way as that in the remote control system. Both terminals transmit video MUs, each of which consists of 4,000 bytes, to each other. Also, they transmit voice MUs, each of which includes 320 bytes, to each other. As in the remote control system, the coding method of video is MPEG-1, and the video consists of only I-pictures. The encoding method of voice is Linear Pulse Code Modulation (LPCM). The transmission rates of haptic media and video are the same as those in the remote control system, and that of voice is 50 MU/s. The bit rate of haptic media is 320 kbps, and the average bit rate of video is 960 kbps, and that of voice is 128 kbps. Each terminal carries out Skipping over received MUs for the intra-stream synchronization control.

4.2 QoE Assessment Methods

4.2.1 Remote Control System

In QoE assessment for the remote control system, each subject wrote a character shown in Fig. 5. The reason why we selected the character is that it has a number of basic elements of using a pen. The subject practiced writing the character several times on the condition that there was no constant delay before the assessment. After the practice, we generated a constant delay for each packet, and the subject wrote the character. The constant delay was changed from 0 ms to 200 ms at intervals of 50 ms. The haptic control scheme and the constant delay were chosen in random order for each subject. The subject was asked to base
Fig. 5  Example of written character when constant delay is 0 ms.

Table 1  Five-grade impairment scale.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Imperceptible</td>
</tr>
<tr>
<td>4</td>
<td>Perceptible, but not annoying</td>
</tr>
<tr>
<td>3</td>
<td>Slightly annoying</td>
</tr>
<tr>
<td>2</td>
<td>Annoying</td>
</tr>
<tr>
<td>1</td>
<td>Very annoying</td>
</tr>
</tbody>
</table>

his/her judgment about the ease of writing in terms of wording used to define the subjective scale (Table 1). He/she gave a score from 1 through 5 to each test to obtain the Mean Opinion Score (MOS) [20], which is one of QoE parameters. Subjects were 15 persons (men and women) whose ages were between 22 and 28. The total assessment time per subject was about 20 minutes.

4.2.2 Remote Instruction System

In QoE assessment for the remote instruction system, after each subject wrote the character shown in Fig. 5 as the student, the subject wrote it as the teacher. One of the authors always acted as the partner (i.e., the teacher or student) of the subject. In each role, the subject practiced writing the character several times on the condition that there was no constant delay. After the practice, we generated a constant delay for each packet, and the subject wrote the character. The constant delay was changed from 0ms to 200 ms at intervals of 50 ms. The haptic control scheme and the constant delay were chosen in random order for each subject. The subject was asked to base his/her judgment about the ease of writing in terms of wording used to define the subjective scale (Table 1). The voice was not used since we let each subject assess only the ease of writing. The subject gave a score from 1 through 5 to each test to obtain MOS. Subjects were 15 persons whose ages were between 22 and 28. The total assessment time per subject was about 60 minutes. The assessment was conducted on different days from the days on which the assessment of the remote control system was done.

5. Assessment Results

5.1 Remote Control System

We show the MOS values of the ease of writing for the remote control system in Fig. 6, where the 95% confidence intervals are also plotted. In Fig. 6, we notice that as the constant delay becomes larger, the MOS values of the position-position and position-force control schemes decrease. The reason why the MOS value of the position-position control scheme decreases is as follows: A large reaction force is presented at the master terminal when the constant delay is large; note that the reaction force is calculated from the gap between the PHANToM stylus position of the master terminal and that of the slave terminal. Therefore, the reaction force increases in proportion to the network delay. On the other hand, in the position-force control scheme, the reaction force is not larger than that of the position-position control scheme, but the direction in which the subject tries to move PHANToM differs largely from the direction of the reaction force received from the student terminal.

We also find in Fig. 6 that when the constant delay is larger than around 0 ms, the MOS value of the position-force control scheme is smaller than that of the position-position control scheme. We show examples of the character written with the two haptic control schemes when the constant delay is 100 ms in Fig. 7, where the shape of the character written with the position-force control scheme is more largely different from the shape in Fig. 5 than that with the position-position control scheme.

5.2 Remote Instruction System

Figs. 8-11 show the MOS values of the ease of writing for the remote instruction system. Fig. 8 plots the MOS values of the teacher when the teacher actively writes the character, and Fig. 9 does those of
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Fig. 6 MOS of ease of writing in remote control system.

Fig. 7 Examples of character in remote control system when constant delay is 100 ms.

Fig. 8 MOS of teacher when teacher actively writes character.

In Fig. 8, we see that as the constant delay becomes larger, the MOS values of the position-position and position-force control schemes decrease. The reason is the same as that in Fig. 6. We also observe in Fig. 8 that the position-force control scheme has smaller MOS values than the position-force control scheme when the constant delay is smaller than around 200 ms.

Fig. 9 MOS of student when teacher actively writes character.

Fig. 10 MOS of teacher when student actively writes character.

Fig. 11 MOS of student when student actively writes character.

Furthermore, we notice that the MOS values of the position-position and position-force control schemes in Fig. 8 are higher than those in Fig. 6 when the constant delay is larger than about 0 ms. This is because in the remote instruction system, each subject at the teacher terminal can write the character with his/her own
whiteboard marker; note that since the master terminal in the remote control system does not have a whiteboard marker, each subject of the master terminal has to write the character while floating the PHANToM stylus in the air at all times.

Fig. 9 reveals that the MOS values of both control schemes are almost the same. The reason is that the reaction force at the student is calculated in the same way for the two schemes (Eq. (1)). We also notice in Fig. 9 that the MOS values of both control schemes are higher than those in Fig. 8. The reason is as follows. When the teacher actively writes the character, the student only tracks the teacher’s movement and does not feel the deterioration in the output quality of haptic media seriously.

From Fig. 10, we find that as the constant delay becomes larger, the MOS value of the position-force control scheme decreases more largely than that of the position-position control scheme. The reason is as follows. As describe dearlier, in the position-force control scheme, the information about the reaction force calculated at the student terminal is sent to the teacher terminal. Then, PHANToM of the teacher terminal is pulled by the reaction force; note that the direction of the reaction force differs from the direction when there exists no network delay. The position information of PHANToM obtained in such a way at the teacher terminal is transmitted to the student terminal, and then the reaction force output at the student terminal is calculated by using the position information. Furthermore, the information about the force calculated at the student terminal is transmitted to the teacher terminal and output. Therefore, both teacher and student feel that the ease of writing is seriously degraded. We show examples of the character written at the student terminal with the two control schemes when the student actively writes the character and the constant delay is 100 ms in Fig. 12, where the shape of the character written with the position-force control scheme is more seriously damaged than that with the position-position control scheme. We also observe in Fig. 10 that the MOS value of the position-position control scheme does not decrease largely. The reason is that the teacher only tracks the student’s movement; thus, he/she does not feel the deterioration in the output quality of haptic media seriously. Also, the MOS value of the position-position control scheme in Fig. 10 is almost the same as that in Fig. 9. This is because in the position-position control scheme, the reaction force is calculated in the same way at both terminals, and each subject does not actively write the character and only holds his/her PHANToM.

In Fig. 11, as the constant delay becomes larger, the MOS value of the position-force control scheme decreases largely. The reason is the same as that in Fig. 10. The MOS value of the position-position control scheme in Fig. 11 is almost the same as that in Fig. 8. The reason is that in the position-position control scheme, the reaction force is calculated in the same way at both terminals, and each subject actively writes the character.

From the above observations, we can say that the position-position control scheme is superior to the position-force control scheme for the remote control system and the remote instruction system.

6. Conclusions

This paper dealt with the position-position and position-force control schemes for two haptic teleoperation systems (i.e., the remote control system and the remote instruction system). We made a comparison between the two control schemes by QoE assessment. As a result, we found that QoE of both
control schemes deteriorates as the network delay becomes larger. We also saw that QoE of the position-force control scheme degrades more seriously than that of the position-position control scheme for both systems, especially when the student actively writes a character in the remote instruction system. Therefore, the position-position control scheme is superior to the position-force control scheme for both systems.

As the next step of our research, we will make the experiment with various types of work and investigate the influences of the network delay on QoE.

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